VIRGINIA TECH

CPES
Center for Power Electronics Systems

2022 DOE Vehicle Technologies Office Annual Merit Review

Heterogeneous Integration Technologies for High-Temperature, High-Density, Low-Profile Power Modules of Wide Bandgap Devices in Electric-Drive Applications

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Project ID: elt242

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Overview

Timeline

- Project start date: April 1st, 2019
- Project end date: March 31st, 2024
- Percent complete: 60%

Budget

- Total project funding: $1.5 M
- Funding for FY 2020: $0.3 M
- Funding for FY 2021: $0.3 M
- Funding for FY 2022: $0.3 M

Barriers and Technical Targets

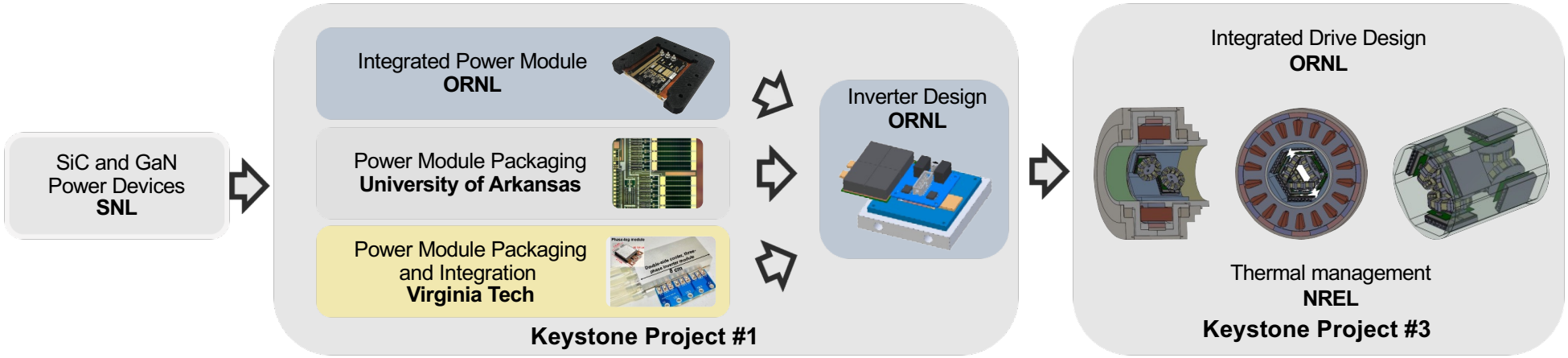
- **Module Packaging:** high-performance bonding materials and assembly technologies (planar, double-sided cooling) for making high-temperature (> 200 °C) power modules to enable high converter power density (> 100 kW/L);
- **Gate Driver:** high-temperature (> 200 °C) intelligent gate driver with integrated current sensor; high-temperature (> 200 °C) gate driver power supply with air-core transformer.

Partners

- Virginia Tech - Lead
- Oak Ridge National Laboratory (ORNL)
- National Renewable Energy Laboratory (NREL)
- DOWA
- University of Arkansas
- SUNY Polytechnic Institute

Relevance and Objectives

- **Goal**
  - ✓ Develop packaging materials, assembly processes, and circuit technologies for making > 200ºC WBG power modules with double-sided cooling capability and intelligent gate drivers with integrated current sensor.
- **Impact**
  - ✓ Enable the EDT consortium to achieve its targets on performance, cost, power density, and reliability of a 100 kW traction drive system.
- **Project Objectives**
  - ✓ Develop a low-cost packaging technology for making double-side cooled WBG (SiC/GaN) power modules with parasitic inductances < 5 nH, heat flux density > 400 W/cm^2, and working junction temperature > 200 °C.
  - ✓ Design and prototype > 200 °C gate drivers with parasitic-inductance based current sensor and protection for module integration.



Approach

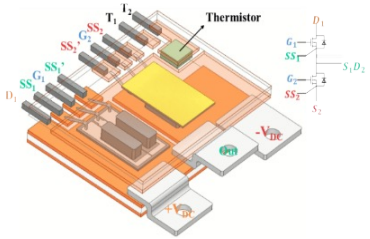
- **Proposed Research:** Design, fabrication, and testing of planar WBG power modules and their integration with gate drivers for electric drives.
- **Technology Summary:** Low parasitic & double-side cooled module fabrication; interconnection by silver-sintering; parasitic-inductance based current sensor integrated in gate driver; air-core transformer for driver power supply.
- **Challenges & Opportunities:** Prototyping yield for design verification; through materials and assembly engineering → low-cost manufacturing

Date	Go/No-Go Milestones	Status
3/31/2021	Demonstrate planar packaging technologies in phase-leg modules of (1200 V, 100-150 A) SiC MOSFET.	Done
9/30/2021	Deliver low-profile 150 °C gate driver boards to ORNL for demo inverter construction.	Done
9/30/2021	Deliver planar, double-side-cooled SiC (1200 V, 100-150 A, 150°C) SiC phase-leg modules to ORNL for demo inverter construction.	Done
9/30/2021	I_phase sensor redesigned for operation at ambient temperature of 150°C and higher	Done
6/30/2022	Prototype and test 200°C power supply for all gate drivers; package and test with gate driver board and power module	On-track

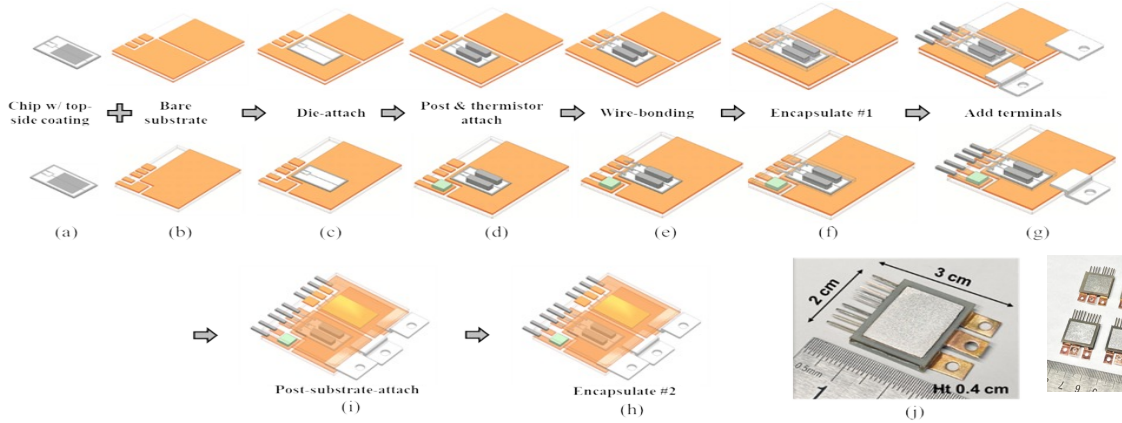
Accomplishments – Double-Side Cooled Power Modules

Double-side Cooled SiC Power Module:

Cree SiC chip: (1.2 kV, 149 A, 13 mΩ)

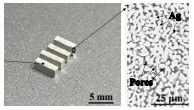


Design



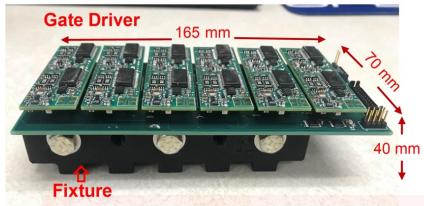
Fabrication

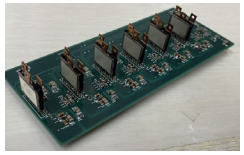
Key Enabler: Porous Ag posts



Prototyping

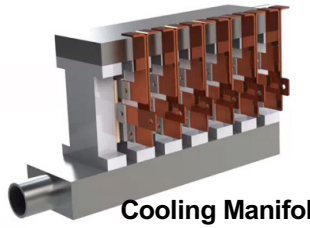
Hardware Delivered to ORNL:



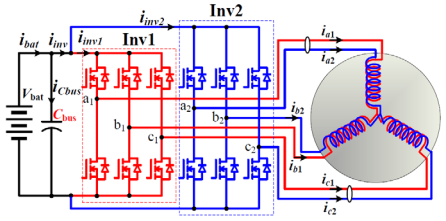


Subassembly with six SiC phase-leg modules mounted on a gate-driver board for ORNL's 100 kW/L inverter.

Under Test in ORNL's Segmented 3-phase Inverter



Cooling Manifold

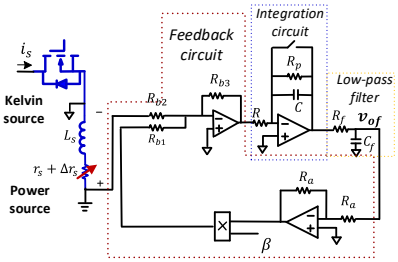


Segmented 3-phase inverter

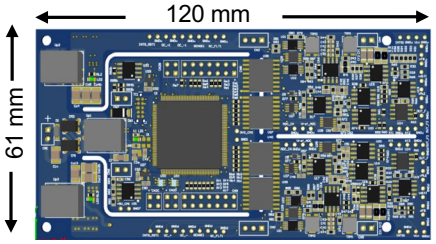
Accomplishments – Current Sensor and Power Supply

Current Sensor

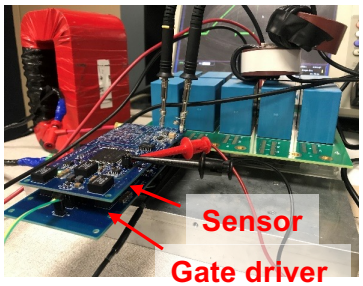
➢ Proposed scheme



➢ Design circuit



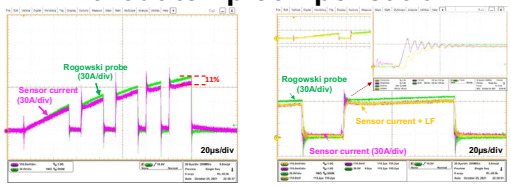
➢ Experiment setup



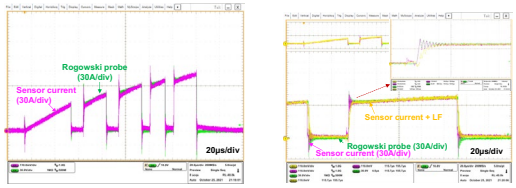
- DPT test
- Case temperature: 150^oC

➢ Results

Without temp compensation



With temp compensation (steady)

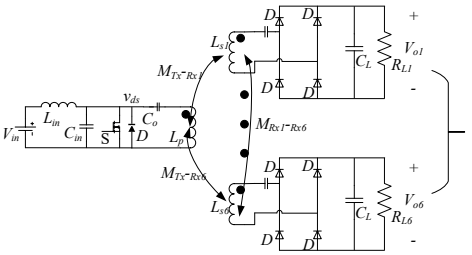


✓ **Temperature effect was compensated.**

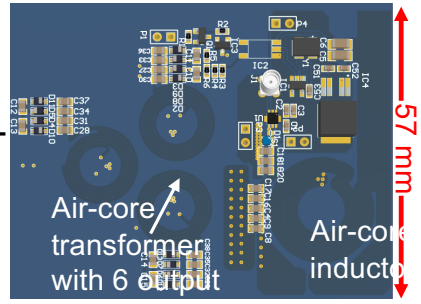
✓ **High-temperature version is being developed.**

Power Supply

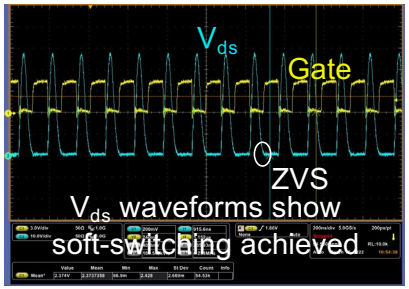
➢ Schematics

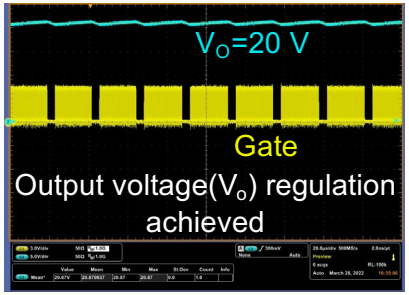


➢ PCB



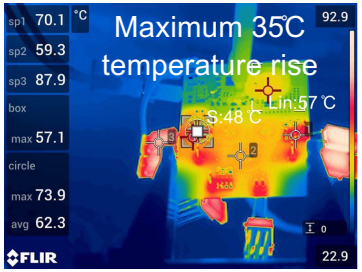
➢ Waveforms





✓ **Six-output transformer was designed as expected.**

✓ **The output voltage regulation was achieved.**



Summary

- **Relevance:** enable the EDT consortium to achieve its targets on performance, cost, power density, and reliability of a 100 kW traction drive system.
- **Approach:** research, develop, and evaluate packaging technologies for making high-temperature, high-density, and low-profile wide-bandgap (WBG) power electronics modules with intelligent gate driver and current sensor.
- **Deliverables:**
  - Working prototypes of double-side cooled SiC (1.2 kV, 149 A, 13 mΩ) phase-leg modules and their gate drivers to ORNL for demonstrating a 100 kW/L inverter.
  - Module design and simulation results, materials processing conditions, assembly procedures, and testing data to DOE and potential module manufacturers.
  - Circuit design, simulation results, and bill of materials for making gate-driver power supply with air-core transformer and gate drivers with parasitic-inductance based current sensor to DOE.
- **Collaborations:** **ORNL**: providing module design specs and supporting on module testing; **NREL**: advising on module thermal management and supporting C-SAM characterization of sintered-metal joints and thermo-mechanical reliability testing; **UArk**: providing high-temperature gate driver chips; **DOWA**: custom-designing and fabricating integrated substrate/heat sink structures for module cooling; **SUNY Poly**: providing SiC power devices.
- **Future Work:**
  - Selection and evaluation of **> 200ºC** module **encapsulant**
  - Fabrication and testing of a gate-driver power supply with air-core transformer for T_j **> 175ºC**
  - Design and testing of a parasitic-inductance based current sensor for T_j **> 175ºC**
  - **Reliability** evaluation by accelerated testing & FEA simulations.

**** Any proposed future work is subject to change based on funding levels.***

Collaboration

ORNL: provide specifications for module design, access to packaging facility, and support on module testing.

NREL: advise on module thermal designs and support C-SAM characterization of sintered-metal joints and their thermo-mechanical reliability testing.

DOWA: custom-design and fabricate integrated substrate/heat sink structures for module cooling.

University of Arkansas: provide high-temperature gate driver chip.

SUNY-POLY: provide SiC power device.

Proposed Future Research

- Prototype and test 200°C power supply for gate drivers; package and test with gate driver board and power module; **[Key Milestone in June 2022]**
- Selection of components and design of the current sensor for **high-temperature operation;**
- Demonstrate planar packaging technologies in phase-leg modules of SiC MOSFETs working at junction-temperature of 200°C;
- **Reliability** evaluation of the double-side cooled phase-leg modules.

**** Any proposed future work is subject to change based on funding levels.***